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Performance-Based Fire Safety Assessment of City Underwater Tunnel

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Abstract

Safe evacuation criterion was first analyzed for fire safety assessment of city underwater tunnel. Then a worst fire scenario of a real underwater tunnel was set up, and simulations on fire smoke spread and people evacuation were carried out based on this scenario. The available safe egress time (ASET) was derived from the fire simulation, while the required safe egress time (RSET) was derived from evacuation simulation. According to the performance-based fire code, fire safety assessment of the tunnel was carried out based on the comparison between ASET and RSET.

Keywords: Underwater tunnel; fire; safety assessment; simulation

1. Introduction

In China, most cities are divided into two parts by a river. With the growth of urban traffic in recent years, river-crossing transportation has become the major bottleneck of the city. In the past, bridges were always used to relieve the pressure of urban river-crossing transportation, but too many bridges would affect the shipping and water environment, so more and more underwater tunnel are built to solve river-crossing transportation problem. Now many long underwater tunnels are under construction or have been finished, such as Wuhan Yangtze river tunnel, Nanjing Yangtze river tunnel, Shanghai Yangtze river tunnel, Xiamen undersea tunnel, Qingdao undersea tunnel and many cross-lake tunnels. As tunnel has long and narrow underground space, smoke from tunnel fire spreads very quickly, it is always difficult to exhaust the smoke. Plus there are few exits to the outside of the tunnel, all these make it difficult to evacuate from a tunnel fire. Once a fire breaks out in the tunnel, it may cause serious casualties [1].

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2. Performance-based Fire Safety Assessment for City Underwater Tunnel

Because there is no special fire code for underwater tunnel fire safety in China at the moment, it needs to assess a tunnel fire safety design using performance-based fire safety analysis method. Performance-based fire safety assessment is mainly based on fire modelling which gets the available safe egress time $T_{ASET,}$ and evacuation simulation which gets the required safe egress time T_{RSET}. In a particular fire scenario, if the available safe egress time is bigger than the required safe egress time, then it is safe for people to evacuate from this tunnel fire. Considering the uncertainty of the modelling and simulation, it always needs to consider an appropriate safety margin during the analysis. Greater the safety margin, safer for people to evacuate from the tunnel fire [2].The quantitative relationship between this two times is shown in figure 1.

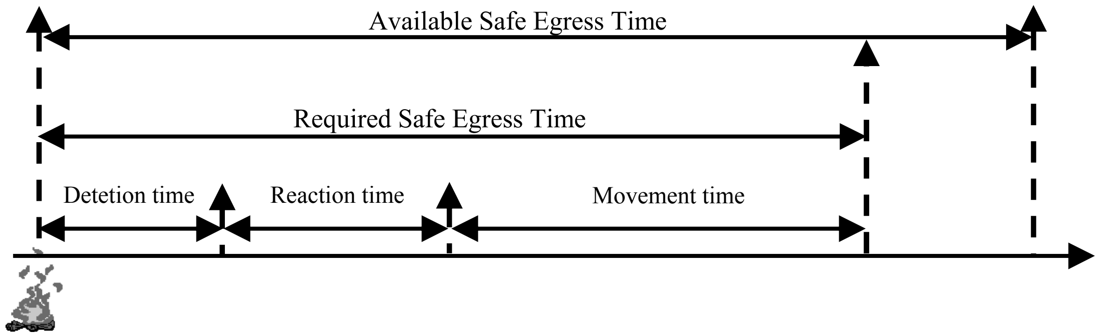

Fig.1 safe evacuation criterion for tunnel fire

When assessing the underwater tunnel fire safety using the performance-based fire safety analysis method, it is very important to choose appropriate indexes which can be used to evaluate the fire safety design. The indexes are limits, or limit ranges for evaluating the fire safety in any given conditions. Normally these indexes include smoke temperature, smoke concentration or clarity, carbon and oxygen hemoglobin (COHb) level and radiation fluxes. Now both at home and abroad, it always adopts smoke temperature, CO concentration and minimum visibility at 2m above the tunnel road as the criterion for people's safe evacuation, as shown in table 1.

Table 1 criterion for people's safe evacuation in a tunnel fire

index	criterion
Temperature at 2m（℃）	≤60
Visibility at 2m（m）	>10
CO concentration at 2m（ppm）	≤1500

3. Fire Safety Assessment of Wuhan Yangtze River Tunnel

Wuhan Yangtze River Tunnel is the first tunnel built across the Yangtze River in China. The tunnel is an urban tunnel with two tubes to lessen the traffic pressure crossing the river. It is about 3600m long and each tube is made up of two cut and cover sections and one shield section. The shield section is about 2500m long and its diameter is 10m. The smoke ventilation strategy is semi-transverse. Fresh air is supplied by jet fans installed in cut and cover sections, and smoke is exhausted through a smoke duct under the tunnel ceiling. The evacuation system in the shield section is comprised of escaping slides leading to the evacuation way under the road surface, and the slides are equipped every 80 meters along the tunnel. The traffic of the tunnel is mainly made up of private cars and passenger cars which carry lots of people every day, so the crowd density in the tunnel is very high. When a fire breaks out in this tunnel, it may cause great casualties and losses. To assess the fire safety of the Wuhan Yangtze River tunnel, a risk analysis was carried out based on the performance-based fire safety method.

3.1 Calculation of available safe egress time

The available safe egress time is normally calculated by fire modelling. After setting a special fire scenario in the Wuhan Yangtze River Tunnel, a fire simulation software is used to model the tunnel fire, then the quantitative values of the characteristic parameters (smoke temperature, CO concentration, visibility, etc.) during the tunnel fire can be derived from the simulation .When these parameters in the tunnel have reached the human tolerance limit, this time is considered to be the available safe egress time. In this paper we adopted the fire simulation software FDS to model the tunnel fire [3]. According to worst case principle, a fire scenario assuming exhaust fans and some jet fans fail to work during the fire was set up, in which the tunnel ventilation system can only produce a longitudinal velocity of 2m/s. In order to save simulation time, a tunnel model with 600 meters long was set up, and the fire lies in 400 meters from the tunnel entrance. There are five evacuation slides in upstream of the fire and two in downstream. As the exhaust system was assumed not working, the duct above the tunnel road was not modelled in the this model , so the tunnel cross section was modelled as a rectangular with 8m in length and 4.8m in height, as shown in figure 2.

As the Wuhan Yangtze River Tunnel only permits cars with no more than 9 seats to travel through, a fire involved with three cars was prescribed, which produced a heat release rate of 8MW. In the simulation, the mesh grid near the fire was set as 0.2m* 0.2m*0.2m, while sections far from the fire were set as 0.4m*0.4m*0.4m, and the material of the tunnel wall was set to be concrete with fire coatings. The total simulation time was 1200 seconds, during which the temperature, CO concentration and visibility values at 2m height above each slide was calculated. Their results are plotted in figure 3-5, and slide NO1 was in the downstream of the fire, while slide No2 to No6 was in the upstream. It shows that the fire won't endanger people's evacuation in the upstream of the fire, even after it broke out for 20 minutes; the temperature, visibility and CO concentration are all in safe area. But in downstream of the fire, the visibility at 2m high above the No1 slide dropped down to ten meters after 400 seconds. It can be concluded that in the worst tunnel fire scenario, the available safe egress time in upstream of the fire is longer than 1200 seconds, however at the No1 slide downstream the fire it is only 400 seconds.

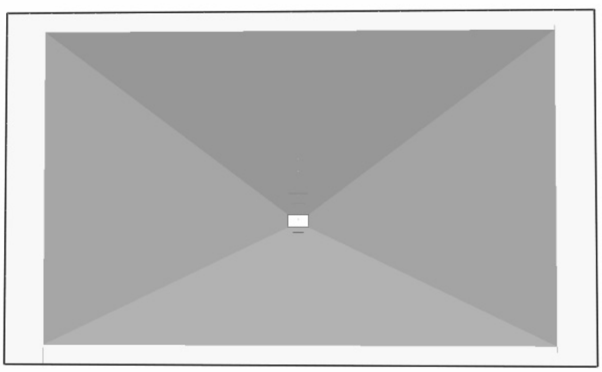

Fig.2 the tunnel model in FDS

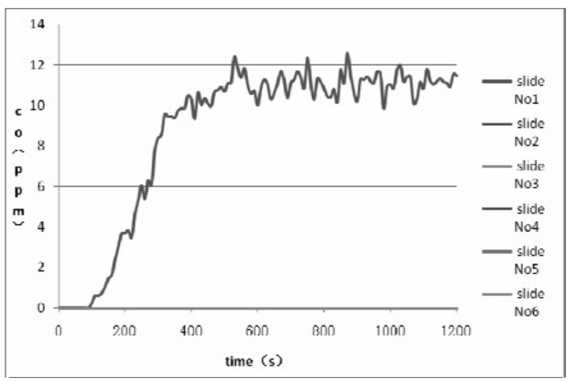

Fig.3 co concentration at 2m above each slide

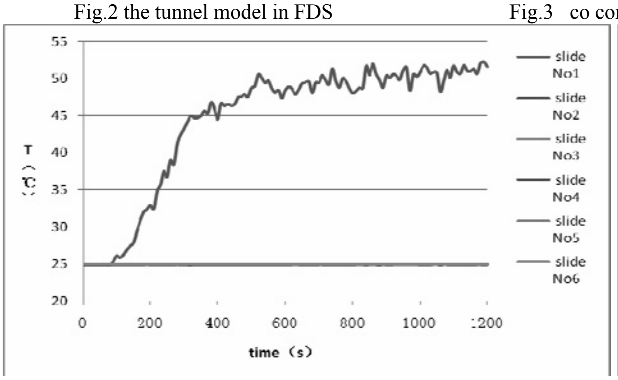

Fig.4 temperature at 2m above each slide

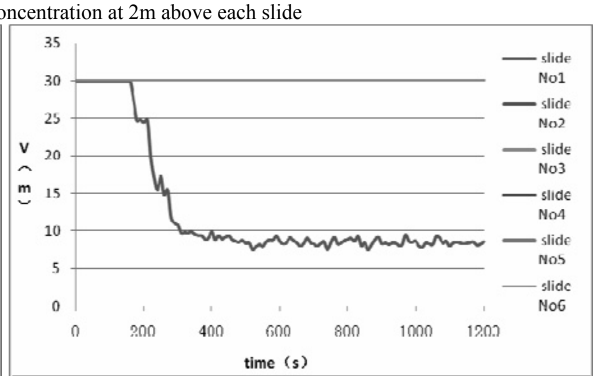

Fig.5 visibility at 2m above each slide

3.2 Calculation of required safe egress time

The required safe egress time is the time that people need to escape from their car to the slide, and then travel through the slide into the escape passageway under the tunnel road. It includes the pre-movement time and movement time. Regarding the pre-movement time, we can assume that people who are near the fire can recognize the disaster more immediately. So this time can be in the range of 2 to 5 minutes based on people's position from the fire. It is assumed that for people between the fire and the first slide, this time is 2 minutes, and 2.5 minutes for people between the first and second slide, 3 minutes for people between the second and third slide, 4 minutes for people between the third and fourth slide, 5 minutes for people between the fourth and fifth slide. In this paper, the evacuation software BuildSGEM was used to calculate the movement time, whose accuracy has been validated [4, 5].

In the BuildSGEM simulation, it is assumed that when the tunnel fire breaks out, there will be a car in every 10m each lane. A small car is assumed having 5 persons, while a bigger car has 9 persons. People need 9-12 seconds to get off the car, and the movement speed in the tunnel is 1.2 m/s. The simulation only includes a tunnel section with 400m upstream of the fire and 100m downstream the fire. According to the simulation result, the time needed for evacuation for each slide section is shown in table 2.

Table 2 the T_{RSET} at each slide

Slide No.	People evacuated	Pre-movement time (s)	Movement time (s)	T_{RSET} (s)
Slide No.1	108	120	236	356
Slide No.2	112	120	249	369
Slide No.3	104	150	240	390
Slide No.4	108	180	238	318
Slide No.5	100	240	230	370
Slide No.6	112	300	245	345

3.3 Performance-based fire safety assessment

According to the calculation carried out above, the comparison between the T_{ASET} and T_{RSET} for the worst fire scenario in the Wuhan Yangtze River Tunnel is shown in figure 6.

Based on the comparison we can conclude that in the worst fire scenario with all the exhaust fans and some jet fans not in function, the available safe egress time upstream the fire is much longer than the required safe egress time. But the safety margin downstream the fire is quite small, because the longitudinal velocity has blown almost all the smoke to the downstream. However, according to the traffic control strategies of the Wuhan Yangtze River Tunnel, the car speed will be 10km/h at least, unless a total traffic jam in the tunnel. But the possibility with both fire and total traffic jam is very small, so cars downstream the fire is able to travel faster than the smoke movement in the downstream. Therefore with the smoke control and evacuation facilities in the Wuhan Yangtze River Tunnel, safe evacuation can be reached.

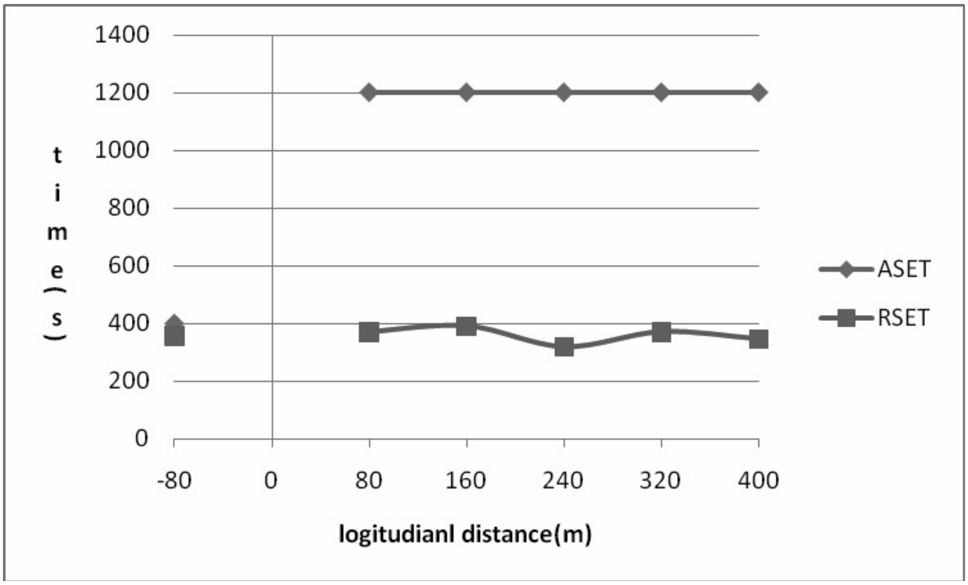

Fig.6 comparison between T_{ASET} and T_{RSET}

4. Conclusions

As there is no special fire code for the increasing underwater tunnel in China, it needs a performance-based fire safety analysis method to assess the fire safety of these tunnels. Based on this method, we carried out fire modelling with FDS and evacuation simulation with BuildSGEM to assess the fire safety of the Wuhan Yangtze River Tunnel. According to the comparison between the required safe egress time and available safe egress time, it is safe for people to evacuate from the tunnel under the worst fire scenario. From the evacuation calculation, it can be seen that the pre-movement time constitutes a big part of the required safe egress time, so it is important for the tunnel to have a good communication system and evacuation guiding system. Once a fire breaks out in the tunnel, the passengers should be informed about it immediately, so as to make the pre-movement time short.

Acknowledgements

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